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by Yu. M. Volynkin, et al.

Paper presented at the XV International Astronautical Congress, Warsaw, September 7-12, 1964

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Translation of "Biologicheskaya otsenka radiatsionnykh usloviy na trasse Zemlya-Luna"

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THE BIOLOGICAL EVALUATION OF RADIATION CONDITIONS ON THE PATH BETWEEN THE EARTH AND THE MOON

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ABSTRACT

This report briefly reviews the physical characteristics of the basic types of cosmic radiation in near earth space, and has determined the quantities of biological doses created by each type of radiation.

It shows that in flight along the trajectory around the moon during the quiet activity of the sun, a shield of 1-2g/cm^2 will provide crew members protection against the danger of irradiation. Protons which are regenerated during a chromospheric flare on the sun represent a real threat to the health and life of the astronauts. Several methods and sources are discussed to protect man from the damaging action of cosmic radiation in his flight from the earth to the moon.

The prospects of the study and conquest of outer space by man, some aspects of which have been formulated by K. E. Tsiolokovskiy, envision the flight of man to the various planets of the solar system.

Apparently the moon is going to be the first celestial body that man will reach in his effort to learn the secrets of the universe. It is natural, therefore, that the study and biological evaluation of physical and radiation conditions that man will encounter in his flight to the moon are of great scientific interest.

It should be noted that numerous studies in this vein have been conducted. The data on various parameters and certain physical factors of near earth space enable us, to a certain degree, to have some conception of the magnitude of the expected danger and of man's capabilities in such a flight. First, we intend to study the composition, the energy spectrum, the space and time distribution of the cosmic radiation, and the biological effects of different types of ionizing radiation.

Definite success has been obtained in the study of the effect of weightlessness on man. The flight of V. F. Bykovskiy, as well as flights of other astronauts, justifies the assumption that man retains his ability to perform different types of functions and can satisfactorily withstand weightlessness longer than five days (Refs. 1, 2, 3).

There is some interesting literature that shows the technological means toward the realization of the idea of man's flight to the moon (Refs. 4,5). However, it is quite apparent that technological, medical and biological problems are far from being completely resolved, and that the statements giving dates for the realization of such a flight between 1967 and 1970 (Ref. 6) should be viewed as a rough guide. Unquestionably it will depend to a great extent on the result of further studies of the physical conditions in interplanetary space, the results of the studies of the moon itself, and a series of solutions of medical and biological problems designed to insure the safety of such a flight.

This study attempts to analyze the radiation conditions in near earth space and to evaluate the dangers of ionizing radiation that man will encounter during his flight from the earth to the moon. Prior to the discovery of the radiation belts of the earth (Refs. 7, 8), the ionizing radiation in space was not considered a factor that could basically affect safety during the flight (Ref. 9). With the discovery of radiation zones, and especially the radiation following chromospheric flares on the sun, cosmic radiation was considered one of the main barriers between man and his efforts to penetrate outer space (Refs. 10, 11, 12).

Cosmic radiation consists of galactic rays (primary cosmic radiation), ionizing radiation of the earth's radiation belts, and the radiation generated by the chromospheric flares on the sun. A special place is allotted in this study to artificial radiation belts formed as a result of the testing of atomic weapons in outer space.

To evaluate the given types of radiation from the point of view of radiation safety, it is necessary to study briefly the composition of each type of radiation, the energy spectrum, the interaction of charged particles with matter, and the biological dose.

Primary Cosmic Rays (PCR)

These rays represent a flux of charged particles primarily consisting of protons coming from outer space practically in their intact isotropic form. At present, it is considered that the PCR consist approximately of 85 percent protons, 13 to 14 percent alpha particles, and 1 to 2 percent particles with a $Z \geq 3$ charge.

It is believed that all primary particles are completely devoid of orbital electrons, that is, they are the nuclei of different elements. The relative abundance of these nuclei in the PCR is close to the cosmic abundance of the corresponding elements, but differs from the latter by having an excess of heavy nuclei, which is particularly characteristic of the composition of the radiation at greater distances from earth. The energy of the particles in the PCR covers a wide range from 20-40 to 10^{12} mev/nucleon.

Even though a great number of experiments was conducted to determine the charge spectrum of the primary particles, the exact form of this spectrum has not yet been established. This is complicated by the low intensity of the PCR and the difficulty of identifying nuclei heavier than helium. From the data obtained with Soviet space rockets, the intensity of primary cosmic rays in interplanetary space varies during the eleven-year solar cycle from 2 (maximum activity) to 4.5 particles cm^{-2} sec^{-1} (Ref. 13).

Let us attempt to evaluate the PCR dose to which the astronaut would be exposed beyond the magnetic field of the earth. The calculated data of the daily dose created by PCR in free outer space according to different particle groups are given in Table 1.

Table 1

Particles or nuclei group	Flow (part. cm^{-2} sec^{-1})	Daily dose (mrad)	Daily dose (mrem)
Protons	1.8	4.9	5.0
α-particles	0.4	5.5	5.5
$L\,(3 \leqslant Z \leqslant 5)$	$1 \cdot 10^{-2}$	0.4	0.5
$M\,(6 \leqslant Z \leqslant 10)$ . . .	$2 \cdot 10^{-2}$	5.5	33.0
$H\,(Z > 10)$	$1 \cdot 10^{-2}$	5.2	96.0
Total	2.24	21.5	140.0

Considering the result of the studies conducted with the space rockets (Ref. 13) in our calculations, we have taken the PCR intensity at 2.24 part cm^{-2} sec^{-1}. The RBE coefficient for different particles was determined on the basis of the graphic dependence of the RBE on the linear energy loss (LEL) cited in the work of H. Rossi (Ref. 14).

Assuming that the composition of PCR for all practical purposes does not change, the daily dose will fluctuate from 125 to 270 mrem depending on the solar activity. This is from 7 to 16 times higher than the maximum permissible daily dose for a man who is daily exposed to the sources of ionizing radiation (Ref. 15). The protective shell of the spacecraft from 1 to 2 g/cm^2 thick will not substantially affect this magnitude.

It should be pointed out that cosmic rays also contain about 1 percent electrons and an insignificant flux of γ-rays, which do not contribute a great deal to the ionization. They can be disregarded in the study of the radiation danger from PCR ionization caused by electrons and γ-rays.

It is known that the magnetic field of the earth deflects a considerable quantity of PCR particles, and therefore the integral dose of PCR in the orbits made by the Soviet and the American astronauts was almost one half the dose encountered in outer space. Table 2 shows the total dosage to which the Soviet astronauts were exposed in their flight on the ship Vostok.

From this table it can be seen that the mean daily dose obtained in the experiment corresponds, within the range of measurement accuracy, to the rated dose. About 85 to 90 percent of the integral dose during this flight is attributed to the primary cosmic radiation, primarily the heavy components in this radiation (Ref. 10).

Table 2

Astronauts	Duration Flight (hours)	Types of Dosimeters					
		ILK (3.2 mm Al)		IKS (0.6 mm Sn)		R-3	
		Dose (mrad)	mrad/days	Dose (mrad)	mrad/days	Dose (mrad)	mrad/days
Gagarin, Yu. A.	1.5	0.5	8.4	—	—	—	—
Titov, G. S.	25	13 ± 2	12 ± 2	—	—	—	—
Nikolayev, A. G.	94	64 ± 1	16 ± 1	58 ± 7	15 ± 2	43 ± 1	11 ± 1
Popovich, P. R.	71	48 ± 1	16 ± 1	51 ± 7	17 ± 2	32 ± 1	11 ± 1
Bykovskiy, V. F.	119	75 ± 2	15 ± 1	81 ± 6	16 ± 1	50 ± 1	10 ± 1
Tereshkova, V. V.	71	48 ± 1	16 ± 1	42 ± 2	14 ± 1	30 ± 1	10 ± 1

Experiments conducted on the returning Sputniks 2 to 5, and on the Vostok 1 to 6 ships, enabled us to make a rather complete evaluation of the cosmic radiation dose and its radiobiological aspects at altitudes of 180 to 320 km. For this purpose various biological subjects ranging from bacteria and microspores all the way up to the dog were used, as were various special methods of investigation (Refs. 16, 17, 18, 19).

The analysis of the results showed that only some changes, primarily in the genetic apparatus, observed in the lysogenetic bacteria, a number of vegetative objects, and Drosophila, can be attributed to the effect of the cosmic radiation.

For example, in the flight of the Vostok 5, which lasted almost five days, a summary radiation dose was registered that equaled about 80 mrad (physical chemical dosimeters) and 50 mrad (gas discharge counter). If we take the RBE coefficient for the heavy component of the PCR as being 10, then the resistance dose expressed in rems, in this case, will be about 450 to 750 mrem. Such a dose can be detected only with the aid of the objects highly sensitive to the radiation and by appropriate tests. Thus, the changes registered, for instance, in the lysogenetic bacteria can be explained, and the absence of radiobiological effects in the other organisms, less sensitive to the radiation, can be understood.

During the flight of a man through outer space, the integral dose of PCR doubles, and after 15 days of flight will amount to from 1.8 to 4 rem. Evaluating this dose as a radiation danger factor in the flight to the moon, it should be noted that it does not exceed the maximum permissible levels of radiation (established for the astronauts), and it is highly improbable that it could seriously affect the health of the man. However, the biophysical characteristics of the effect of heavy nuclei, associated primarily with the capacity of the particles to produce a high ionization density in the final segment of the flight path (the "shock" phenomenon), should be borne in mind. In connection with this it can be supposed that the penetration of the heavy nuclei into the hypothalamus region of the brain, the lens, the retina, etc. can cause damage to a large group of cells and, consequently, upset the thermoregulatory functions, cause a cataract, microscotoma, etc.

The "shock" phenomenon represents a new type radiobiological action, the study of which has only begun. At present there are more or less convincing facts showing the effect of the heavy components, their effect in flight as well as in the laboratory experiment on small biological objects and individual cells. There is a complete absence of experimental data on the effect of local injuries to individual organs and centers on the organism as a whole. On the basis of some theoretical computations (Refs. 20, 21, 22) and the results of the biological experiments conducted with the Soviet and American rockets (Refs. 18, 23, 24, 25), it can be assumed that the probability of such a local effect on separate cell groups, even if it does exist, is relatively small and will not produce any significant effect in flights of several weeks' duration.

Ionizing Radiation of the Radiation Belts of the Earth

The radiation of the internal belt consists of protons whose spectrum changes according to the law $N(>\varepsilon) = K.E.^{-\gamma}$ with the indicator γ = 1.84 and electrons. Maximum intensity for different data is as follows: protons from $2 \cdot 10^4$ part cm^{-2} sec^{-1} to 10^5 part cm^{-2} sec^{-1}, and for electrons with E_e > 20 kev--$2 \cdot 10^8$ part cm^{-2} sec^{-1}. The thickness of the belt with a high radiation intensity equals about 4,000 to 5,000 km. In taking off from the earth the spacecraft will go through this belt for about 15 minutes. The median dose created by protons along the orbit through the internal belt will equal about 5 rem/hr inside the spacecraft shielded by 1 g/cm^2. Thus, the electrons of the internal radiation belt will be deflected by this shielding, and the dose intensity caused by bremsstrahlung will constitute about 0.1 rad/hr.

The radiation of the internal belt primarily consists of electrons from E_e to 20 kev to several bev. The intensity of electrons with an energy of E_e >40 kev in the center of the belt equals 10^8 part cm^{-2} sec^{-1}. The radiation in this belt will not have a decisive effect on the total dose, even though the flight of the spacecraft through this belt lasts about two hours. This radiation with its shield of 1 g/cm^2 will equal 0.2 to 0.3 rad and is attributed to bremsstrahlung.

Electrons detected by the Soviet researchers (Ref. 26) beyond the boundaries of the external belt are completely deflected by the shield and have no effect on the integral dose because of the insignificant amount of energy they possess.

Thus, an astronaut aboard the spacecraft, shielded by 1 g/cm^2, flying across the natural radiation belts along the trajectory around the moon will be exposed to a total dose of radiation of the order of 2.5 to 3.5 rem. This dose together with the BCR dose does not constitute a threat to the health of the astronaut.

In the artificial belt, the radiation intensity, spatial distribution of radiation and the lifespan of injected particles depend on many factors which at present cannot be calculated by theoretical means. The predictions made on the basis of individual experimental factors in many cases have not been borne out.

The measurements of doses in the center of the artificial belt created as a result of the atomic explosion conducted by the United States on July 9, 1962, have shown the presence of high levels of radiation in this zone. Thus, with a shield of 4.5 g/cm^2, the intensity of the radiation dose two months after the explosion constituted 3 rad/hr, and after four months it was 35 rad/hr. With a shield of 0.4 g/cm^2, the dose intensity two months after the explosion equaled 2,000 rad/hr, and after four months was equal to 30,000 rad/hr. Measurements conducted in the same zones one year after the explosion have shown that during this period the high level of radiation continues. The dose intensity, shielded by 3 g/cm^2, amounted to 17 rad/hr (Ref. 27).

Therefore, the nuclear explosion of July 9, 1962, created a big enough zone in which the electrons pose the same danger as do the protons in the external belt. The future behavior of the artificial belts is rather difficult to predict, and therefore the danger of radiation during an actual flight can be evaluated only after the direct measurements of the radiation levels in this area have been made. If the flight will take place along the trajectory circling the moon, then, considering the conditions described above, the astronaut in his flight through the artificial belt shielded with 1 to 2 g/cm^2 would be exposed to the dose of the bremsstrahlung in the order of 2 to 3 rem.

Radiation Caused during the Chromospheric Flares on the Sun

This radiation consists of about 90 percent protons and 10 percent alpha particles. In some of the flares, the presence of heavy nuclei with a charge up to Z = 18 (Ref. 28) was observed.

The flares of solar protons can be arbitrarily classified into three groups according to their intensity and the energy spectrum of radiation: high energy, medium energy and low energy.

The high energy group of flares includes those whose secondary radiation can be observed on the earth at sea level. The proton energy in such flares reaches 20 bev, it lasts several dozen hours and its intensity is relatively low. Among such flares are those occurring on February 28 and March 7, 1942, July 25, 1946, November 19, 1949, and February 23, 1956. The last flare was maximal. It is characteristic that these flares took place within the decrease or the increase in solar activity. On the average, they occur every four or five years.

The flares of July 10 and 16, 1959, and November 12, 1960, are examples of medium-energy flares. The energy of protons in such flares reached several bev. They occur 2 to 4 times during the year when the solar activity is high. To the third group can be assigned flares of the type that occurred on August 22, 1958, May 10, 1959, and July 14, 1959; the proton energy of these flares reaches several hundred mev. These flares occur 10 to 12 times a year.

The solar flares are divided into seven classes according to their optical brightness ($1, 1^+, 2, 2^+, 3, 3^+, 4$). The generation and ejection of protons with dangerous radiation usually follows flares of the optical class 3 and 3^+.

To determine the degree of radiation effectiveness of the protons of the solar flares in calculating the protection against them, it is necessary to know the flow and the energy spectrum throughout the whole phase of the flares, especially during the maximum intensity phase of the flow, since the basic increase in the dose occurs during this particular period. Also, it is necessary to know the direction of the flow of the basic mass of the charged particles.

At present several authors have made calculations of the doses and determined the necessary protection against the proton radiation of all classes of flares. The calculated quantities of dose, and consequently the recommendations for physical protection vary greatly depending on the nature of the original data used for the calculations, the conditions of the flight, etc. However, in all of these calculations, regardless of the way they have been conducted, one thing is very apparent: a high degree of danger from the protons of solar flares, especially in flights beyond the magnetic field of the earth.

For example, in order that the integral dose not exceed 100 rem, it is necessary to shield with 13 g/cm^2 against the flare of the class that occurred in February, 1956; 15 g/cm^2 against the flare that occurred in May, 1959; and 2 g/cm^2 against the flare that occurred in August, 1958. To lower the radiation dose to the maximum permissible level, e.g., 25 rem (Ref. 11), it is necessary to increase the shield from 32, 25 and 2.8 g/cm^2 against the above-mentioned flares. It is quite apparent that the solution of this requirement encounters great and, at present, unresolvable technical difficulties (Ref. 36).

Therefore an astronaut in outer space, having a shield of 3 g/cm^2, can find himself within the area of the dangerous radiation caused by the solar flare, and will be subjected to a dose exceeding 10 and reaching several hundred rad. Naturally the question arises of how can the biological aspects of these doses be evaluated? It is known that with a single exposure to radiation under the conditions on earth, a dose of about 25 rem causes definite changes in the organism: in the circulatory system and the central nervous system. And the dose of about 100 rem causes a primary reaction, in the form of nausea, fatiguability, a reduced capacity to work and other symptoms. A single exposure to a radiation dose of 200 rem in 50 percent of the cases causes typical, sharp solar plexus pain followed by nausea, vomiting, dizziness and the loss of the ability to work. Lethal results as a rule are observed in the exposure to radiation in the dose of about 300 rem, however they can also be caused by lower doses. The flight conditions apparently will affect the reaction of the organism to the action of ionizing radiation. However, the evaluation of these peculiarities at the beginning of and during the exposure is at present rather difficult.

The radiobiological effectiveness depends on many factors: the quantities of the absorbed integral dose; type of radiation (density of ionization); time of the radiation action (intensity of the dose); and, also on how the organism was exposed, in part or in whole as well as the functional condition of the organism and its radio resistance.

The action of the protons from the solar flares probably will have the effect of their radiation diminished by two factors: the prolonged duration of the effect (low intensity of dose), and the presence on the ship of various screens preventing total irradiation. At the same time several conditions during the flight--emotional strain, changes in the composition of the surrounding gases, etc.--will diminish the radio resistance of the organism and increase the effect of the radiation.

A considerable amount remains unclear in respect to the effect of weightlessness on radiation reaction. First experiments in this field give us a basis to conclude that the effect of cosmic radiation can be summed up with the action of prolonged weightlessness (Ref. 29). Evaluating the duration and the initial radiation, the factors acting during the period of flight and the factors that affect the organism during the descent of the ship should be kept in mind. This, first of all, pertains to the overloading of the heart and the circulatory system. the resistance of which considerably diminishes under the effect of ionizing radiation.

The relative biological effectiveness of radiation (RBE) of the solar protons can at present be determined only by the indirect method, on the basis of the calculated data, and the results obtained from the laboratory experiments conducted with different proton accelerators.

From the analysis of the experimental results obtained by several authors (Refs. 30-34), it has been concluded that the RBE coefficient for the proton of the solar flares, if we keep in mind the radiation spectrum as a whole, should be more than one (about 1.5). In evaluating the integral dose to which the astronaut was exposed during the particular flare, it should be kept in mind that under certain conditions this dose may be increased by the secondary neutrons, whose RBE factor will not be less than 2.

Recapitulating the above, it can be considered that under flight conditions the radiation effect will be complicated by the actions of several factors (the reinforcement coefficient not less than 1.5), and that this condition must definitely be taken into consideration in establishing the maximum permissible radiation levels for the astronauts in developing the protective measures.

It is quite apparent that the main sources of acute overradiation of the astronaut beyond the magnetic field of the earth will be the protons of the solar flares.

What is the probability of the ship being in the area of dangerous radiation from the flare and, consequently, the overexposure of the astronaut in flight along the trajectory around the moon? This probability depends on the mean probability of the occurrence of the flare and the duration of the flight. During a week-long flight, such danger is relatively high, and constitutes about 16 percent for the flare of the type that occurred on August 22, 1958; 5.8 percent for the flare that occurred on May 10, 1959; and 0.3 percent for the flare that occurred on February 23, 1956 (Ref. 35). During the period of increased solar activity, and longer duration of the flight, this danger increases.

Thus we have briefly reviewed the physical characteristics of the basic types of cosmic radiation, and have determined the quantity of the biological doses (primarily their upper limits) caused by every type of radiation. According to our data, the integral radiation dose from PCR, natural radiation, and artificial radiation of the belts encircling the earth, behind a shield of 1 to 2 g/cm^2, should not be above 10 rem for the two-week flight along the trajectory around the moon. In case of an accident forcing the return from the height of approximately 75,000 km along the most unfavorable trajectory, the highest possible dose will be about 20 rem (Ref. 36). Consequently the shield of 1 to 2 g/cm^2 will satisfactorily insure the radiation safety for the members of the crew, if the flight takes place during the calm period of solar activity.

The protons of solar flares represent the real threat to the health and the life of the astronaut. In this case, for the purposes of increasing safety from radiation, it would be logical to increase the physical shield to 3 g/cm^2, which, when compared to the flare of the type that occurred on August 22, 1958, would diminish the integral dose to the maximum permissible level (Refs. 11, 15). The problem of physical protection against protons generated by flares of the type that occurred on July 10, 1959, and February 23, 1956, is extremely complicated, and at present apparently has no technical solution.

Reviewing the question of the physical protection of the astronaut against the effect of the ionizing radiation, it is necessary to keep in mind two conditions that are pointed out in a number of experiments (36-29). Thus, in designing the spacecraft, the possibility of using various designs of the ship, storage of fuel, water, food, and so on, should be considered for this purpose. And second, in determining the maximum measures of protection, it is necessary to take into consideration the high energies and the variegated composition of the PCR and solar radiation. In a number of cases it is not feasible to increase the thickness of the shielding as this may not lower, but increase the integral dose (Ref. 40). Great significance should be attached to the physical properties of materials and to their form in calculating this protection.

Aside from physical protection, the danger of proton radiation during solar flares can be diminished by an attempt to predict their occurrence. The existing methods of prognosis at present allow prediction accuracy of up to 75 percent two to three days prior to the flare's occurrence. This time is rather short, and, consequently, the problem of prognosis should be studied intensively; apparatus for these predictions should be developed and set up at various points on the earth, and also on the spacecraft.

Secondly, the resistance of the organism to the actions of the protons of solar flares can be basically increased by different pharmacological and chemical preparations (Refs. 11, 12, 41). Successful research in this field justifies the hope that the pharmacological and chemical protection of the astronauts against the ionizing radiation will be one of the main achievements in the system of measures to insure against the danger of radiation in the space flight.

In conclusion, it should be noted that progress in the study of space is tied in with further accumulation of data about the physical aspects and the characteristics of the factors of interplanetary space, as well as their biological evaluation under the conditions of flight experimentation. Much attention should be focused on the biological indications of new trajectories for space flight.

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